The Ionisation of Heavy Gases by X-Rays.

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(Communicated by Sir J. J. Thomson, F.R.S.—Received February 17,—
Read March 23, 1911.)

Introductory Remarks.

When the term "rays" or "radiations" occurs alone in the following paper, it must be understood to mean "X-rays" or "X-radiations." The term "corpuscular rays" is limited to those corpuscles which have a velocity high enough to allow them to ionise atoms against which they strike. Corpuscles whose velocity is too small to enable them to ionise atoms will be referred to as "δ-rays."

When X-rays pass through matter, energy is absorbed from them and is known to be re-emitted in the following forms:—(1) δ-rays, (2) corpuscular rays, (3) characteristic X-rays, (4) scattered X-rays. Various relations have been found connecting the emission of these forms of energy with the substances in which they originate and with the nature of the X-rays used to produce them.

Let us consider a characteristic X-radiation produced in any substance by X-rays from any source, and let us determine the penetrating power of this radiation for a substance which does not emit a characteristic radiation—say, carbon. Then we shall define rays of higher order as those which have a greater penetrating power than this characteristic radiation, and rays of lower order as those which have a smaller penetrating power.

We may now formulate two important relations, due to Barkla and Sadler, and to Sadler, respectively:—

1. Characteristic rays can only be produced in a substance by incident rays when the latter are of higher order.*

2. The corpuscular radiation from a substance exposed to X-rays is increased when that substance is emitting its characteristic X-radiation.†

The quantitative relations, however, between these various radiations have not been fully investigated. Also the mechanism involved in the conversion of the energy of X-rays into energy of ionisation in gases is uncertain. The latter problem has been attacked by two investigators, but with contradictory results.*

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* Barkla and Sadler, 'Phil. Mag.,' May, 1909.

† Sadler, 'Phil. Mag.,' March, 1910.

The following paper contains the results which the author has so far obtained in the investigation of these questions in the case of gases.

First Method of Investigation.

The gas used was contained in a vessel C, whose lower side was made of thin parchment paper, so that the X-rays were but slightly absorbed on entering. The region in which ionisation took place was a shallow cell D, 10 cm. in diameter and usually 1·6 cm. high. Its parallel walls were made of tightly stretched paper, and the whole vessel C was lined with aluminium covered with paper to reduce corpuscular and X-radiations from the cylindrical walls as much as possible.

A Röntgen bulb was placed at A (fig. 1), and at B various metals were used to produce known characteristic radiations. The pressure of gas in C was varied and the change in the ionisation in D measured by an electroscope, which was an improved form of one previously described by the author.†

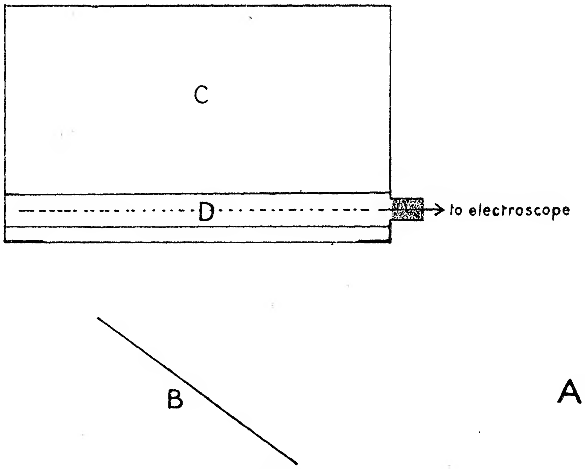

Fig. 1.

Let us now consider what form of curve is to be expected when ionisation is plotted against pressure, the ionisation taking place in a shallow vessel with parallel boundaries and filled with a gas which is uniformly ionised.

Let I_0 = intensity of incident X-radiation, *i.e.*, energy per cubic centimetre in the incident beam. Let βI_0 = rate at which corpuscular energy is liberated per cubic centimetre of the gas at normal temperature and pressure (N.T.P.). Then $\beta I_0 p \Pi^{-1} dx$ = energy produced per second in a layer of thickness dx at pressure p, where Π = atmospheric pressure.

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* Crowther, 'Roy. Soc. Proc.,' March 10, 1909, A, vol. 82, p. 103; Bragg, 'Phil. Mag.,' September, 1910, p. 406.

† Beatty, 'Phil. Mag.,' November, 1907.

The portion of this energy absorbed between the layer and the upper boundary is

$$\beta I_0 p \Pi^{-1} [1 - e^{-\lambda(d-x)}] \, dx,$$

where d is distance between parallel boundaries and λ is coefficient of absorption of the corpuscles by the gas at pressure p.

Integrating we find that the total corpuscular energy absorbed per second between the bounding planes is

$$\beta I_0 p \Pi^{-1} [d - \lambda^{-1} (1 - e^{-\lambda d})].$$

Now let αI_0 be the energy which appears per cubic centimetre of the gas per second as ions, other than those produced during the absorption of the corpuscular energy.

Then when the pressure of the gas is p, the energy absorbed per second in this way is $\alpha I_0 p \Pi^{-1} d$. Hence total energy absorbed per second is

$$I_0 p \Pi^{-1} \{ (\alpha + \beta) d - \beta \lambda^{-1} (1 - e^{-\lambda d}) \}. \quad (1)$$

Now Lenard* has shown that the coefficient of absorption of corpuscular rays by matter is proportional to the density of the matter through which they pass, so that $\lambda_0 p = \lambda \Pi$, if λ_0 is the coefficient at atmospheric pressure. Also, to connect equation (1) with the amount of ionisation produced, let us assume that the same amount of energy is required to produce an ion whether the ionising agent be corpuscular rays or X-rays, and let n molecules be ionised by the expenditure of one erg, each ion so produced carrying a charge $\pm e$. Then when unit amount of energy is absorbed in producing ionisation a charge ne is given to the electrode. The ionisation produced by secondary X-radiations from the gas in the experiments to be described is very small and may be neglected.

Hence, from equation (1) we get ionisation, y, per second given by

$$y = neI_0 p \Pi^{-1} \{ (\alpha + \beta) d \} - ne\beta I_0 \lambda_0^{-1} \{1 - e^{-\lambda_0 p d \Pi^{-1}}\}, \quad (2)$$

which may be written as an expression involving p only,

$$y = Ap - B(1 - e^{-\kappa p}). \quad (3)$$

Now when the pressure of the gas is above a certain limit the exponential term in equation (3) may be neglected, and the equation reduces to

$$y = Ap - B. \quad (4)$$

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* Lenard, 'Wied. Ann.,' 1895, vol. 56, p. 255.

A comparison of the experimental curves with equation (3) will show whether corpuscular rays are produced during the ionisation of the gas. Experiments were made with $Ni(CO)_4$ and AsH_3. When radiations from silver, tin, and iodine were used curves were obtained of the form given by equation (3). The constants A, B, κ, depend of course both on the gas and the kind of radiation to which it is exposed.

Figs. 2 and 3 show two of the curves obtained. These curves thus indicate the existence of an easily absorbed radiation in the gas. Further, since the values of λ calculated from the curves agree with those previously obtained for the corpuscular rays excited in metals by the radiations from silver and tin,* we must conclude that the radiation is corpuscular.

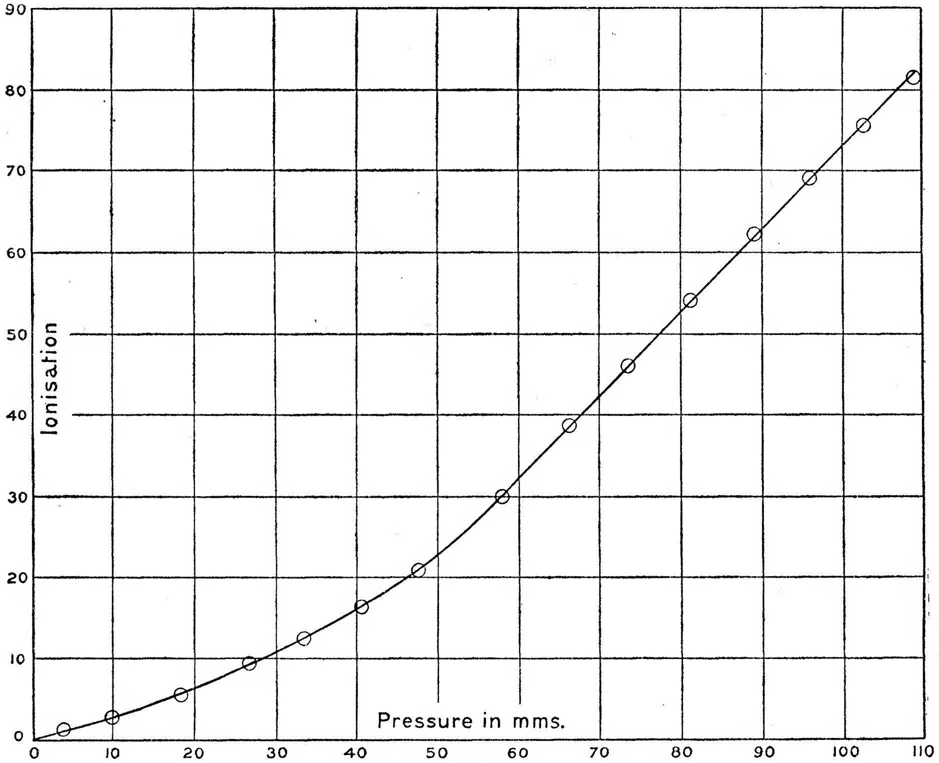

Fig. 2.—Ionisation in $Ni(CO)_4$—Ag Radiator.

In order to calculate λ and β/α from the curves let us go back to equation (4). When $y = o$ then $p = B/A$. Hence if the linear part of the curve in fig. 3 be produced to meet the axis of p

$$OA = B/A = 76\beta\{(\alpha+\beta)\lambda d\}^{-1}.$$

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* Sadler, 'Phil. Mag.,' March, 1910.

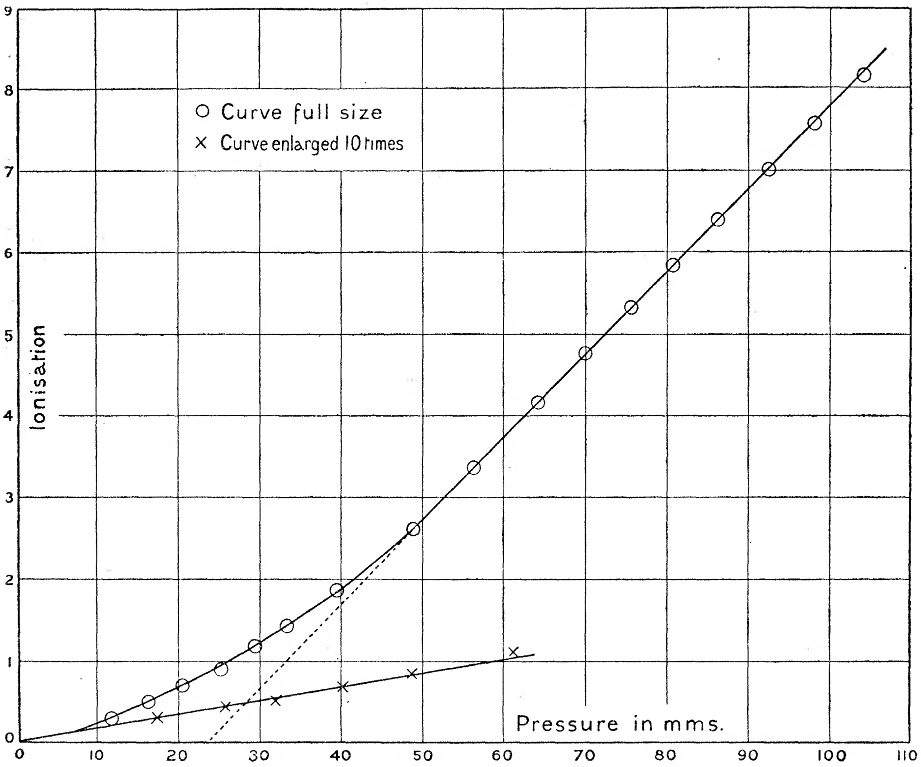

Fig. 3.—Ionisation in AsH_3—Sn Radiator.

Also from equation (2) it appears that the final slope of the curve divided by its initial slope, *i.e.*, $\tan\phi/\tan\theta$, is equal to $(\alpha+\beta)/\alpha$.

Hence we can calculate λ and β/α. These numbers were calculated in several cases and found to be in agreement with those found by the more direct method which will now be described.

Second Method of Investigation.

In equation (4) the term B results from the fact that corpuscular rays produced in the gas in the layer next to the bounding walls are stopped by those walls before their energy is entirely spent in producing ions. If the walls themselves emitted corpuscular rays at a sufficient rate to balance this loss then ionisation would become proportional to pressure. We shall now show that, if the walls of the vessel be lined with a film of the same substance as is used in the gaseous state in the chamber, this condition should be realised. For example, we might use AsH_3 in a chamber which is lined with a film of As. It is necessary that the film should be so thick that corpuscular rays produced at one of its surfaces should not be able to penetrate the thickness of the film so as to emerge at the other surface.

Now let βI_0 as before be the rate at which the energy of the incident rays is converted into corpuscular radiation per cubic centimetre of gas at N.T.P. Also let λ_0 be the coefficient of absorption of the corpuscular rays by the gas at N.T.P., and let D be the density of the film relative to that of the gas. Then we may assume that $\lambda_0 D$, $\beta I_0 D$, are the corresponding quantities for the film. But, assuming an exponential law of absorption, if corpuscular energy is produced per cubic centimetre of film at a rate $\beta I_0 D$, then $\beta I_0 D/\lambda D$ or BI_0/λ is the rate at which it will escape from each square centimetre of the film surface.

Of this energy $\beta I_0 \lambda^{-1}(1-e^{-\lambda d})$ will be absorbed per second by the gas in the chamber, and on adding this quantity to the right-hand side of equation (1), we finally get the following modification of equation (3) :—

$$y = Ap.* \tag{5}$$

In obtaining equation (5) it has been assumed that the corpuscular rays travel initially in the direction of the incident X-rays, and no account is taken of those which are deflected through more than 90° in the course of their flight. The argument would be incomplete if no account were taken of these deflected rays, but sufficient generality may be attained in the following way:—Let us assume that the corpuscular rays are initially projected in all directions. Consider those whose initial direction of motion makes with the direction of the incident X-rays an angle lying between θ and $\theta + d\theta$. Let the rate at which energy appears per cubic centimetre of gas in the form of corpuscular rays travelling in this direction be $\beta I_0 f(\theta)\, d\theta$. The author has shown† that when corpuscular rays are produced in a film of silver by X-rays which fall normally on the film, the coefficient of absorption by air of the corpuscular rays emerging from the upper surface of the film is the same as for those emerging from the lower side. We may then assume that λ is the same for each bundle of corpuscular rays, no matter what its initial direction may be.

Hence the expression $\beta I_0 \lambda_0^{-1}(1-e^{-\lambda d})$ will be replaced by

$$\int_0^{\pi} \beta f(\theta)\, d\theta\, I_0 \lambda_0^{-1}(1-e^{-\lambda d \sec\theta}).$$

But on applying the same correction to equation (1), the last term in that equation will give exactly the same integral with the sign reversed, so that the two expressions under the sign of integration cancel each other when added, and we have as before $y = Ap$.

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* This equation has been also deduced by Prof. Bragg by a similar method. 'Phil. Mag.,' September, 1910, p. 402.

† Beatty, 'Phil. Mag.,' August, 1910.

Hence under these conditions the film radiates just enough corpuscular energy into the gas to balance the corpuscular energy lost by the gas to the walls, and ionisation becomes proportional to pressure.

In order to test equation (5), films of As and Se were deposited on the inner surfaces of the walls of the chamber when the gases AsH_3 and SeH_2 were used. Of course in these cases the film was not exactly the same substance as the gas, but the effect of the hydrogen atoms in AsH_3, for example, is quite negligible as regards ionisation effects, while the change in λ produced should entail quite a small effect and only at low pressures. Indeed, in the experimental curves it was found impossible to detect irregularities due to this cause.

When curves connecting ionisation and pressure were now drawn, it was found that in every case the curve was a straight line through the origin (fig. 4). Since a curve representing equation (5) can only be obtained if the assumption made in obtaining this equation is true, *i.e.* that the amount of corpuscular radiation produced in a substance is independent of its physical condition, we can now draw the following deductions :—

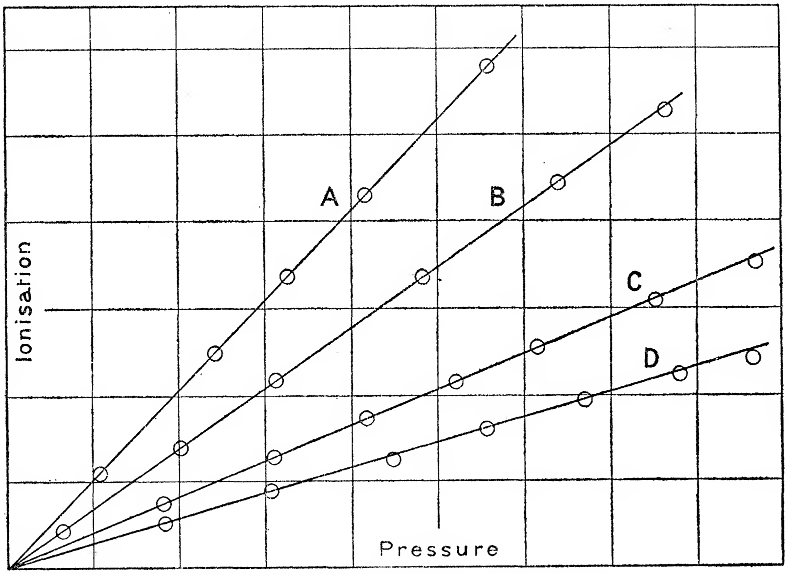

FIG. 4.—A, Ionisation in SeH_2—Sn Radiator.
B, „ AsH_3—Sn Radiator.
C, „ SeH_2—Mo Radiator.
D, „ AsH_3—Mo Radiator.

(1) When $Ni(CO)_4$, AsH_3, SeH_2, are ionised by radiations of higher order, corpuscular radiation is produced in the gas or vapour.

(2) This corpuscular radiation is produced in the same quantity per gramme of the substance, whether the substance is in the solid or gaseous condition.

With regard to these deductions there is no reason to suppose that Ni, As, Se, are exceptional in their behaviour towards radiations, and there is much evidence to show that the above conclusions may be extended to many other chemical elements.

The next step was to find how much of the ionisation in the gas was due to the ions formed during the absorption of the corpuscular radiation produced in the gas. Consider a vessel, 1 cm. in height, containing air, and bounded by two parallel films of Se. Let i be the ionisation produced per second by the incident X-rays in the air in the vessel. Let Ri be the ionisation per second in the air due to corpuscular radiation from the films. Then

$$Ri = ane\beta I_0 \lambda_0^{-1}, \tag{6}$$

where a is the combined area of the films, and λ_0 is the coefficient of absorption of the corpuscular rays by SeH_2 at N.T.P.

Now, if ρ is the density of SeH_2 relative to that of air at the same pressure, and μ the coefficient of absorption of the corpuscular rays by air, then, assuming Lenard's law,

$$\lambda_0 = \rho\mu. \tag{7}$$

On eliminating λ_0 from (6) and (7) we get

$$R\mu\rho = ane\beta I_0/i. \tag{8}$$

Now βI_0 is the rate at which corpuscular energy is produced in SeH_2 per cubic centimetre, so that the right-hand side of equation (8) represents the ionisation per cubic centimetre in SeH_2 due to corpuscular radiation, relative to that in air at the same pressure due to the incident X-rays.

The following experiments were made to find R and μ. The chamber C (fig. 1) was filled with air, and the inside of the ionisation vessel was lined with a film of Se. The air-pressure was varied, and ionisation plotted against pressure. Fig. 5 is a type of the curve obtained.

In Fig. 5, c evidently represents the ionisation due to corpuscular energy from the films.

b represents the ionisation in air at 760 mm. pressure, due to the incident X-rays. Since the ionisation vessel was 1·6 cm. in height, $b/1·6$ represents the ionisation in a space 1 cm. thick. Hence $1·6\ c/b = R$. Also μ, the

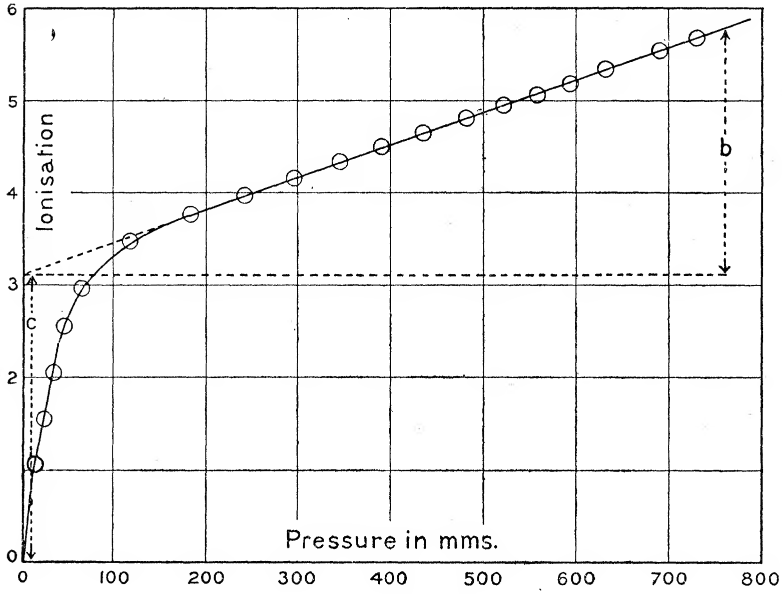

Fig. 5.—Se Radiator.

coefficient of the corpuscular rays from the films, can be determined from the curve in fig. 5 in the manner described in a previous paper.*

The values of $R\mu\rho$ are given in Table I, Column 4. To obtain the total ionisation in SeH_2 relative to that in air, the ionisation in the vessel was measured at different pressures when the vessel was occupied by (1) pure SeH_2, (2) air. The ratio of the slopes of the linear parts of the curves thus obtained gives the total ionisation in SeH_2 relative to that in air for any particular radiator.

The values of the relative total ionisation are given in Table I, Column 5.

Table I.—Ionisation in SeH_2 relative to that in Air.

Radiator.	R.	λ.	Ionisation due to corpuscular rays = $R\lambda\rho$.	Total ionisation.	Total ionisation minus corpuscular ionisation.
Fe	Values not yet completely determined			30·3	
Cu				29·2	
Se............				30·6	
Sr............	1·98	16·1	92	122	30
Mo	2·56	14·0	103	190	87
Ag	4·78	8·8	121	231	110
Sn	7·2	6·5	135	250	115
I	10·8	5·9	183	286	103

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* Beatty, 'Camb. Phil. Soc. Proc.,' vol. 15, Pt. 5, p. 416.

Examination of Table I.

From Column 5 we see that the ionisation in SeH_2 relative to that in air remains constant till the characteristic X-radiation of Se is evoked. When radiations of higher order are used the ionisation is greatly increased.

Let us now consider the corpuscular energy coming from the films. When radiations of lower order are used an easily absorbed radiation is emitted from the films, but it is not yet certain that it is entirely corpuscular, and at present no quantitative results are given for it in the table. When we pass to radiations of higher order a large increase of corpuscular energy is found, accounting for the greater part of the whole ionisation produced.

To what is the remainder of the ionisation due, *i.e.*, the ionisation given in Column 6? It cannot be accounted for by the absorption of the characteristic X-radiation produced in SeH_2, for at the pressures used the fraction of this radiation absorbed is negligible.

Three possibilities, at least, present themselves. The remainder may be due to the direct formation of ions by the incident X-rays, to a discharge of δ-rays from the atom at the moment when the corpuscle leaves it, or to a similar discharge due to the disturbances produced in the atom by the excitation of the characteristic radiation.

Experiments are now in progress to determine the amount of energy emitted by the gas in the form of characteristic radiation. The results so obtained will assist in deciding between the possibilities mentioned. The emission of corpuscular rays when radiations of lower order are used is also being closely examined. From results already obtained it seems that these rays may account for an appreciable fraction of the whole ionisation, even when the characteristic radiation is not evoked.

Summary.

1. When X-rays pass through AsH_3, SeH_2, or $Ni(CO)_4$, a large part of the ionisation produced is due to the production of corpuscular rays.

2. The corpuscular rays are produced in the same quantity from these substances whether they are in the solid or the gaseous condition.

3. The case of SeH_2 has been closely examined and quantitative results found for the fraction of the total ionisation due to corpuscular rays.

I desire to thank Prof. Sir J. J. Thomson for his interest in and helpful criticism of the above work.